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A.S.W.E.
TECHNICAL NOTE

RX2-61-3

THE SECOND FOLDED WAVEGUIDE AERIAL FOR FREQUENCY SCANNING RADAR

(Title - Unclassified)

by

D. P. R. Roessler

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ADMIRALTY SURFACE WEAPONS ESTABLISHMENT
Portsdown, Cosham, Hants.

A.S.W.E. TECHNICAL NOTE RX2-61-3

DATE: 6TH JULY, 1961

THE SECOND FOLDED WAVEGUIDE AERIAL FOR FREQUENCY SCANNING RADAR

by

D. P. R. Roessler

Approved by J. Croney
Head of Division

SUMMARY:

A frequency scanning aerial is described which offers an improved far-field radiation pattern. Further study of the constructional problem is imperative if there is a serious requirement for this type of aerial.

Admiralty Surface Weapons Establishment,
Portsdown, Cosham,
Portsmouth, Hants.

FIGURE NUMBER	REFERENCE NUMBER OF DRAWINGS OR PHOTOGRAPHS	SECURITY CATEGORY	FIGURE NUMBER	REFERENCE NUMBER OF DRAWINGS OR PHOTOGRAPHS	SECURITY CATEGORY
1 2	A263000	Unclassified	16	L60/439	Unclassified
			17	A263009	Unclassified
3	L62/250	Unclassified	18	A263010	Unclassified
4 5	A263001	Unclassified	19	L62/253	Unclassified
6	A263002	Unclassified	20	A263011	Unclassified
7 8	A263003	Unclassified	21	A263012	Unclassified
			22	A263013	Unclassified
9	A263004	Unclassified	23	L62/254	Unclassified
10	A263005	Unclassified	24	L62/255	Unclassified
11	L62/251	Unclassified	25	L62/256	Unclassified
12	L62/252	Unclassified	26	L62/257	Unclassified
13	A263006	Unclassified	27	L60/440	Unclassified
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7, 8	A263003	Unclassified	22	A263013	Unclassified
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LIST OF CONTENTS

LIST OF ILLUSTRATIONS

THE SECOND FOLDED WAVEGUIDE AERIAL

FOR FREQUENCY SCANNING RADAR

1. INTRODUCTION

A radar beam may have its direction changed without mechanical means by using a technique usually called "frequency scanning". In order to cover a wide angle of scan in this way, within the limited tuning range of current high power transmitters, the aerial must be made to have an enhanced sensitivity to frequency changes. This sensitivity may be obtained by folding a waveguide into the form of a "jumping cracker" and allowing it to radiate in a controlled manner from a line of slots cut in the waveguide, (Fig. 1). A fan beam is thus produced which may be scanned widely in the plane of the array by altering the frequency of the transmitter.

Collimation in the plane transverse to the array may be arranged with a cylindrical parabolic mirror having its line-focus occupied by the array of slots. Alternatively, each slot of the frequency sensitive array may be made to couple energy at a given rate into a waveguide linear array. The planar "array of arrays" thus produced radiates a pencil beam which scans in the plane of the frequency-sensitive array of feeds.

2. BASIC DESIGN

In order to establish the techniques of frequency scanning in A.S.W.E. it was decided in 1955 to produce a demonstration set as quickly as possible, even if the small effort available meant that the system might be rather crude.

The aerial design consisted of a folded waveguide array feeding a narrow mirror as a suitable mirror had already been developed for use in Type 982.. It was thought best to remove the array from the reflected beam by "off-setting", in order to reduce sidelobes in the plane transverse to the focus of the mirror (Fig. 2). The only way of doing this was to arrange the radiating slots so that one was cut in each alternate bend of the folded waveguide, thus forming a linear array.

2.1 Folded Waveguide Array

The first choice of radiator was a "shunt displaced" slot cut parallel to the centre-line of the waveguide, and having its radiated power controlled by its displacement from the centre-line. This type of radiator has often been used in straight waveguide applications. A full acount of earlier work with the shunt displaced slot in folded waveguide has been given in Reference 1. Scanning of the beam was accomplished substantially as predicted, but sidelobes were much higher than was expected. This paper therefore begins with a critical study of the first choice of radiator.

2.2 Possible Defects

It was first suspected that the square box surrounding each shunt displaced slot, (Fig. 3), was causing other modes to propagate from the slot. Three modes are possible, H_{01}, H_{10} and H_{11}. (Fig. 4). It then seemed obvious that, if the H_{11} mode existed at all, it would propagate along the short waveguide formed by the box, at a phase velocity different from the other two modes. The emergent wave would then have a phase error along the length of the array proportional to the amount of excitation of the unwanted mode. It seemed reasonable that the excitation of the unwanted mode would be a function of the slot displacement, and a phase error was therefore expected, having a curvature somewhat similar to the amplitude distribution (cosine²) imposed along the array. Phase measurements on a 5 ft long array showed that such a phase error was unmistakably present.

Simultaneously, measurements in different planes of the radiation pattern of a single radiator showed that the maximum power was propagating in a plane at an angle to that containing the axis of the guide. This was not altogether surprising since it was the first experiment to prove the existence of an unwanted H_{11} mode. However, the beam from an array of these skew radiators must suffer from the alternately skewed radiation; higher sidelobes would be formed consistent with the reinforcement of radiators spaced at alternate slot intervals. The individual radiations are sketched in Figure 5a.

It is extraordinarily difficult to devise any experimental means of proving the existence of the H_{11} mode, because both the H_{01} and H_{11} modes may exist. Attempts were made with wire and strips to suppress all but the wanted mode and to note any difference in phase and amplitude plots. These experiments served only to strengthen the idea that the shunt-displaced slot at the base of a square waveguide box was not the right approach to the problem.

3. A NEW RADIATOR

The first ideas for an improved aerial array began with the need for a new radiator which would:-

(a) propagate no higher order modes;

(b) radiate maximum power in one plane, irrespective of the power radiated and the sense of the excited field;

(c) have minimal phase change with power radiated;

(d) avoid the gable-shaped corners between each limb of the waveguide;

(e) dispense with the separate boxes previously used above each slot.

A series of experiments proved that (a) and (b) could be satisfied by cutting a series-inclined slot in the centre of the gable corner used in the first jumping cracker. (Fig. 5b). In order to satisfy (d) and (e), thus attaining a simple mechanical construction, series-inclined slots were tried; these were cut in a flat plate like the broad face of a waveguide, with the jumping cracker underneath. (Fig. 6). This was highly successful and requirement (c) was also satisfied. A more detailed account of some of the important steps follows.

3.1 Matched Square Corner

The simplest way to connect two pieces of waveguide which are joined face to face is to cut away some of the common wall and place a flat plate on top. As far as r.f. is concerned, a strong reflexion would occur which could be adjusted, but not removed by varying the height, h, between the common wall and the flat top. (Fig. 7). Sparkover would of course occur at quite low power. Whilst attempting to reduce the likelihood of breakdown by rounding the top of the common wall, it seemed sensible to exaggerate this radius to form a capacitive iris and so simultaneously to match the 180° corner. (Fig. 8).

For size 10 waveguide using the waveband chosen for the interim aerial, this was highly successful and proved to be an important advance in the work which followed. The v.s.w.r. of the final corner shows a match of 0.99 at mid-band and 0.97 at each end of the band. (Fig. 9). This was considered quite adequate for the purpose; in fact, this result was slightly better than that with the gable corners. (Fig. 10). Sparkover did not occur for peak powers of 1.5 MW at atmospheric pressure.

3.2 Series-inclined Slot in Square Corner

The superiority of the series-inclined slot over the shunt-displaced slot, lay in having a radiator always centred on the centre-line of the array. Moreover, the speed of experimental work was greatly enhanced by the ease of having a given length of slot in a central disk which could be rotated into any desired angular position and hence offer any desired radiated power. (Fig. 11). No other slotted radiator has this property. Furthermore, the disks could easily be removed and different sizes of slot cut without difficulty or undue wastage of material.

It was first necessary to find out

(a) whether the new radiator had a smooth resonance curve

(b) whether the peak could be brought on to mid-band by altering the length of the slot

(c) whether tuning was flat enough over the band

(d) whether the slot and corner withstood r.f. power without sparking.

Using a single slot on one square corner, tilted at 20° from the longitudinal axis of the guide, it was soon established that a slot, $2\frac{1}{8}$ in x $\frac{1}{4}$ in overall, $\frac{1}{8}$ in radius at each end, gave a smooth resonance curve. A flat maximum centred near 10.9 cm wavelength was achieved; this wavelength represents mid-band in the aerial design. The unslotted corner withstood 1.5 MW peak r.f. power at atmospheric pressure. With a slot this figure fell to $\frac{3}{4}$ MW for small angles of inclination, and even to $\frac{1}{2}$ MW for larger angles, but at this stage the slots were not rounded at the edges; for a practical application such rounding would be an obvious improvement. With the corner and slot established, a folded waveguide array of twelve slots in square corners, (Fig. 12), was specified in November, 1957.

3.3 Characteristics of Slot

The twelve slots were cut in disks above the centre of each square corner, and were thus easily turned to any given inclination to the centre line of the guide. With the slots set alternately at $\pm 15^{\circ}$ and a reflexionless load at the end of the folded waveguide preceded by a small probe, power was fed into the array and the level at the load end noted. All the slots were then covered with metal foil. Each slot in succession was then uncovered and the power drop due to radiation through the slot was noted. The difference between doing this consecutively and in a random fashion was observed. (Fig. 13). This confirmed that the preliminary measurement of a fairly high v.s.w.r. within the guide was correct.

Systematic measurements were then made, changing the angle at which all the slots were inclined. Each array then had twelve slots all at one angle. The object was to measure the radiated power through any one slot at a given angle of inclination, in a typical position along the array where mechanical errors and representative but undesirable electrical reflexions within the guide would be encountered. There is little hope of workshop or factory producing a perfect array; the best that can be achieved is to have it carefully made and to know what sort of behaviour it will exhibit in the presence of the imperfection.

It was found sufficient to use as few as eight slots in the array, and from these an average radiated power for the angle of inclination was established. (Fig. 14). An experiment was also made to show the variation over the band of frequencies to be used; it was found to be encouragingly small. Small dots in Fig. 14 show the spread.

A graph was then plotted of the normalised conductance of a typical slot against its angle, (Fig. 15); it can be seen that over the working range this is a straight line. From this graph slot angles were read off to suit the conductances calculated for a 12-slot array having a ($\frac{1}{5} + \frac{4}{5}$ cosine^2) distribution. This is a far quicker procedure than establishing a "conductance law" analytically and calculating slot angles to decimals of a minute. The accuracy of the experimental work and the resulting graph seldom warrant such a task, and the final radiation patterns rarely give good agreement with those predicted. Mechanical errors in construction are, in any event, of the same order as those derived from a carefully plotted graph. It is therefore very doubtful whether the time-honoured procedure of calculation has anything to commend it.

4. TWELVE ELEMENT ARRAY

4.1 Radiation Patterns

Using the graph in Fig. 14, the twelve slot angles which would give the desired distribution were set up, the disks were soldered in place, and the array patterns were measured in the field. Two important features were immediately evident; the array gave sidelobes which were a nearer approach to the theoretical pattern than those of any of the slotted arrays previously used, and the beam scanned through the broadside position without deterioration of the pattern. (Fig. 16). The former is particularly important because with few slots in an array large deviations from the theoretical pattern are usually expected. That these did not occur is considered to be the result of each slot being decoupled from the next within the guide, by the length of folded waveguide in between. In a conventional straight array of slots coupling internally and externally is expected, because complex fields exist in the vicinity of each slot; since they lie about half a wavelength apart interference or mutual coupling is inevitable. Greater emphasis has usually been given to the external coupling, but this folded array provides important evidence to the contrary. The jumping cracker construction provides slots which externally are the usual distance apart but internally are separated by some several half-wave lengths. A later experiment with identical slots and the same distribution cut in straight waveguide showed the same sort of departure from theoretical patterns when measured in the far field.

The second feature, the scan through broadside, was most interesting because no measurements had been made of the equivalent waveguide length around each corner. Each folded arm of the jumping cracker was in fact slightly too short for the scan to occur entirely to one side of the normal. (Fig. 17). Since the wavelength which gave a beam normal to the aperture could be established with some accuracy, it was not necessary to measure the equivalent length around the corner, because at this wavelength an exact number of half wavelengths exists between each slot and the next. A simple calculation gave the correction to apply in future arrays. A further experimental check was performed by observing the wavelength at which the lowest v.s.w.r. was obtained.

4.2 Restriction of Transverse Beamwidth

All the effort so far had been directed towards producing a folded waveguide array which would give acceptable radiation patterns in the plane of the array; it was also essential to narrow the beam in the plane transverse to the array in order to illuminate the parabolic mirror efficiently.

Two parallel plates half a waveguide-width apart were used and these were flared some 3 inches from the slots into a longitudinal horn aperture. The narrow parallel plate region precluded any transmission in unwanted modes. The size of the horn was chosen to offer a useful beamwidth, whilst preserving a "matched horn" condition at the throat. (Figs. 18, 19). Nevertheless, the slot characteristics were found to have altered because the slots now radiated into a bounded medium; accordingly, they were re-measured by the same method as before (Fig. 20). Radiation patterns in the transverse plane are shown in Figure 21. The beamwidth is clearly a maximum at the wavelength giving broadside radiation, and decreases as the beam is scanned to either side. Some error must be allowed in these measurements owing to the need to tilt the array in its own plane in order to align the beam on the distant source. The variation obtained would probably cause some small change in the gain of the final aerial.

The array patterns were taken again with the flare in position and with the slots inclined with the angles appropriate to the revised distribution. These patterns are shown in Figure 22 and should be compared with those is Figure 16, which shows the patterns taken with the array before the horn section was fitted.

5. FABRICATION OF FIFTY ELEMENT ARRAY

5.1 R.F. Loss

The final measurement required before designing a new array was that of r.f. loss per unit length of waveguide. This was found from a section of the first aluminium jumping cracker mentioned in section 1; it had proved a mechanical failure, owing to differential expansion in the dip-brazing bath, but it was decided that it would be preferable to use its actual loss in the calculation of the new array, rather than to adopt some theoretical figure. A loss of 0.025 dB between each slot was derived and used in the calculation.

5.2 Simplified Mechanical Design

The new 50-slot array was designed in four sections giving a final length of 12 ft 6 in. Each section was made from flat aluminium plates held apart by walls, each wall replacing a pair of the waveguide walls in the first folded waveguide array. (Fig. 23). The slots were added in a specially flanged front portion, which could be drilled to receive the longitudinal horn. (Fig. 24). A flat plate completed the non-radiating side of the assembly. (Fig. 25).

5.3 Completed Array

The complete array has fifty slots arranged to give a ($\frac{1}{8}$ + $\frac{7}{8}$ cosine^2) distribution of field along the array. Fig. 26 shows the array assembled at the focus of the parabolic mirror for which it was designed; the longitudinal horn, (Ref. 2), is clearly visible.

5.4 Radiation Patterns

The small team which did the work leading to the specification of the array was dispersed before manufacture commenced. Others completed the window design (Ref. 2) and measured the far-field patterns. (Fig. 27). These patterns are not as good as the very promising patterns of the 3 ft brass array. There can be no doubt that the discrepancies are largely due to mechanical inaccuracies.

Should there be a definite requirement for this type of array the greater part of the effort should be allotted to the mechanical means of attaining the simplicity and accuracy of brass waveguides stuck together. Some of the mechanical difficulties encountered and the techniques used have been reported in Reference 3.

6. CONCLUSION

An improved radiator for the interim frequency scanning radar has been developed which gives unusually small phase errors on transmission. Using an array of only twelve of these radiators, a brass waveguide frequency-scanning aerial has been made which produces radiation patterns in good agreement with theoretical predictions. This shows that careful construction can reduce phase errors to acceptable levels. If the same mechanical accuracy could have been attained in the 50-element aluminium array which followed, the patterns obtained might have been even better. The next problem in this investigation is therefore largely a mechanical one.

7. ACKNOWLEDGEMENTS

Work on the series-inclined slot began in October, 1957; the 12 ft array of 50 slots was specified in May, 1958. That so much was done in such a short time was largely due to the enthusiasm and hard work of those who performed the experiments - Messrs. G. D. W. Bowyer, J. Flower, . Y. Pottage, E. A. O. Ritson. The author would also like to acknowledge valuable discussion with Mr. P. J. Houseley and the design work of Mr. D. Foster.

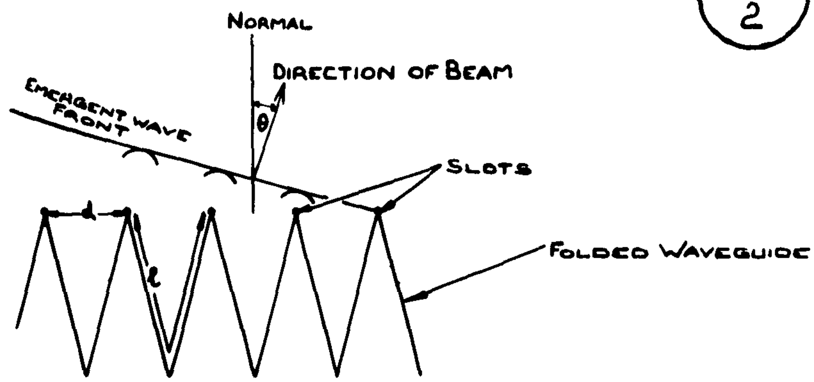
8. REFERENCES

1. Houseley P. J. and Roessler D. P. R. "An Interim Aerial for a Frequency Scanning Radar". A.S.W.E. Technical Note RX2-61-2.

2. Porter N. E. and Ward H. L. H. "The Design of a Frequency Scanning Array in Folded Waveguide". A.S.W.E. Technical Note RX2-60-3.

3. Foster D. "The Mechanical Development of a 12 ft 6 in Folded Waveguide Assembly for an S-Band Radar". A.S.W.E. Technical Note RX2-59-15.

1/2



$$\sin\theta = \frac{\lambda}{d}\left\{\frac{\ell}{\lambda_g} - \frac{2p+1}{2}\right\}$$

λ = WAVELENGTH IN AIR.

λ_g = " " WAVEGUIDE.

$p = 0, \pm 1, \pm 2$ ETC.

FIG. 1 INCREASE IN FREQUENCY SENSITIVITY

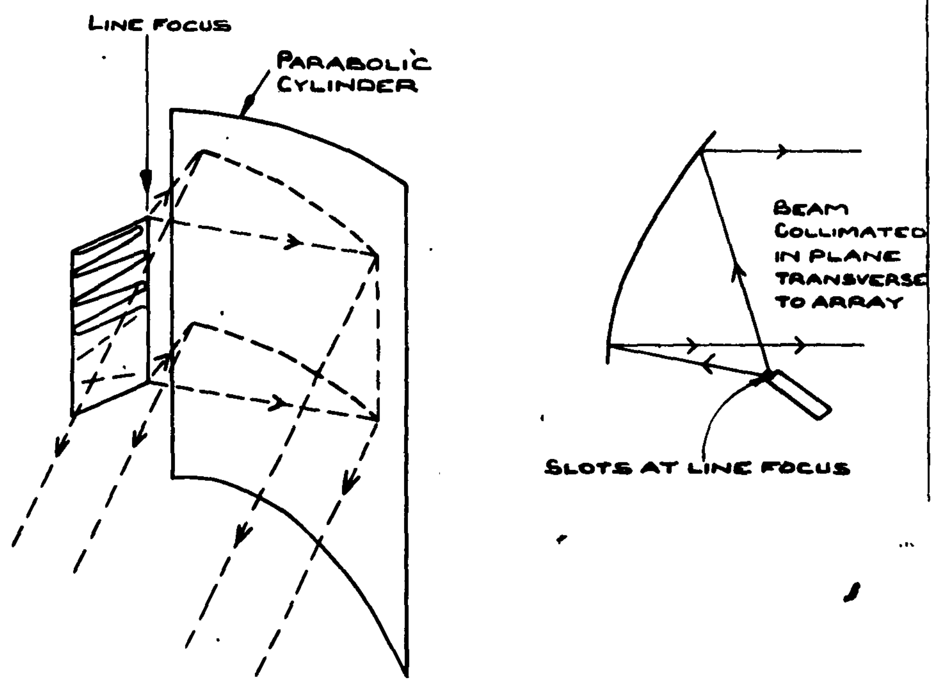
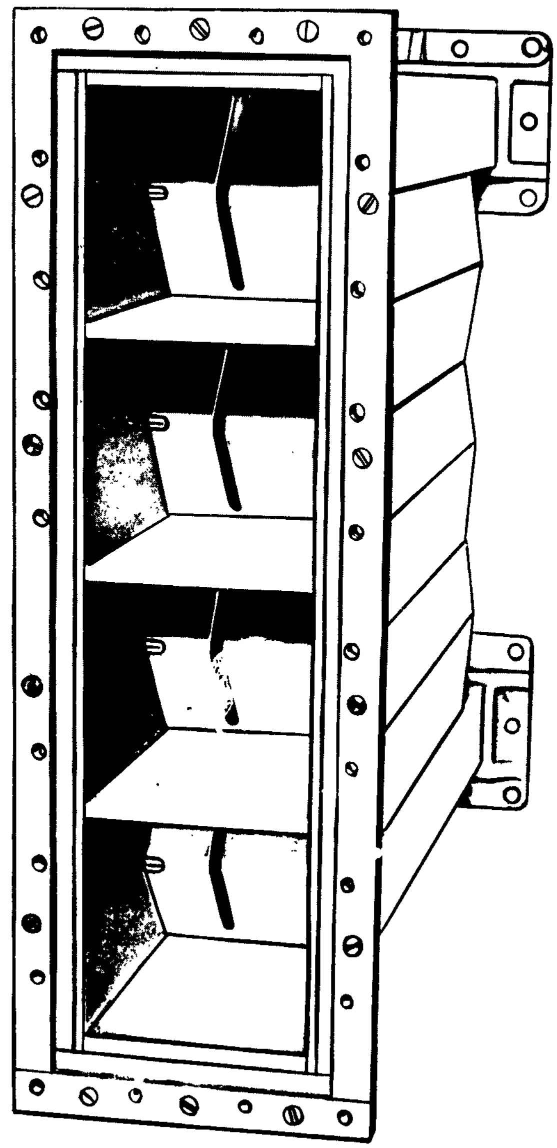


FIG. 2 OFFSET MIRROR

RX2-61-3



SHUNT DISPLACED SLOT IN
SQUARE WAVEGUIDE

RX2-61-3

L62/250

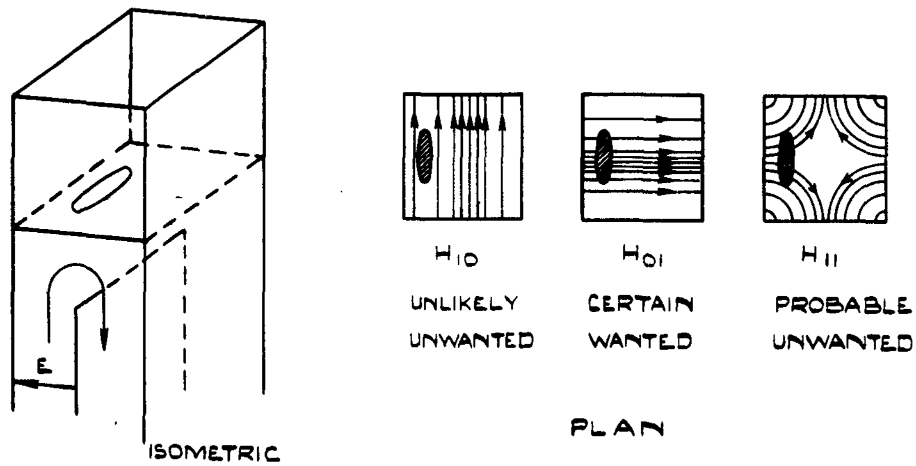


FIG 4 MODES OF RADIATION FROM A SQUARE WAVEGUIDE HORN EXCITED BY SHUNT-DISPLACED SLOT

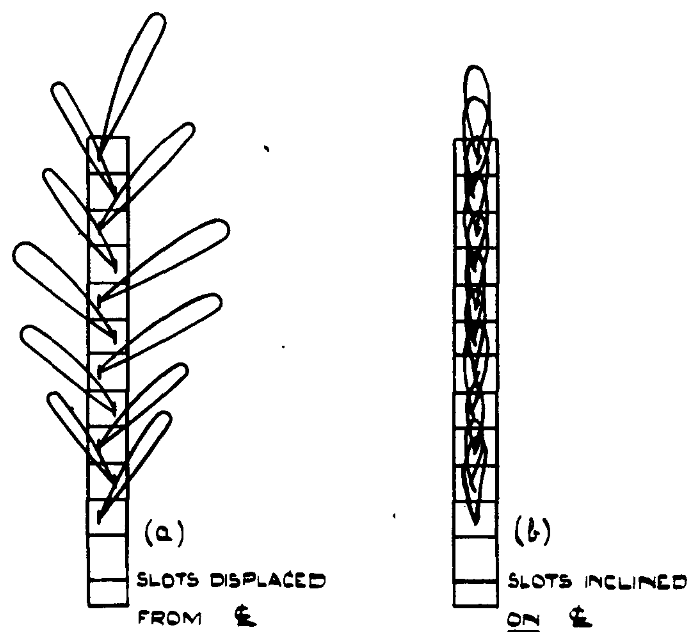


FIG 5 BEAMS FROM INDIVIDUAL RADIATORS

RX2-61-3

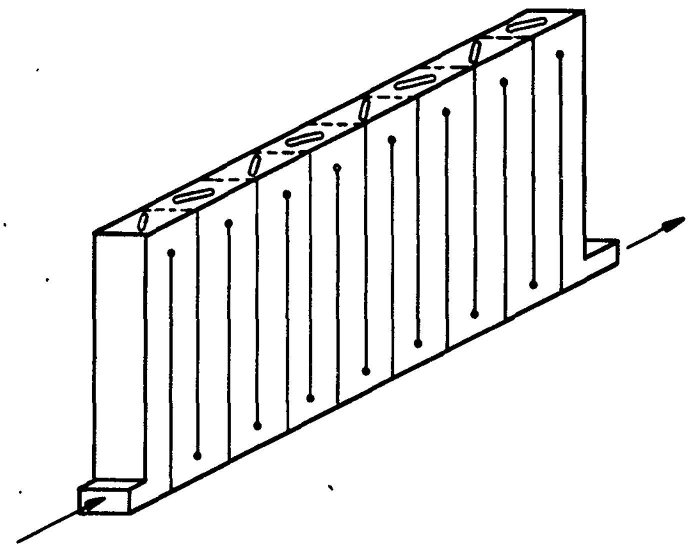


FIG. 6 FOLDED WAVEGUIDE WITH SERIES INCLINED SLOTS CUT IN SQUARE CORNERS

RX2-61-3

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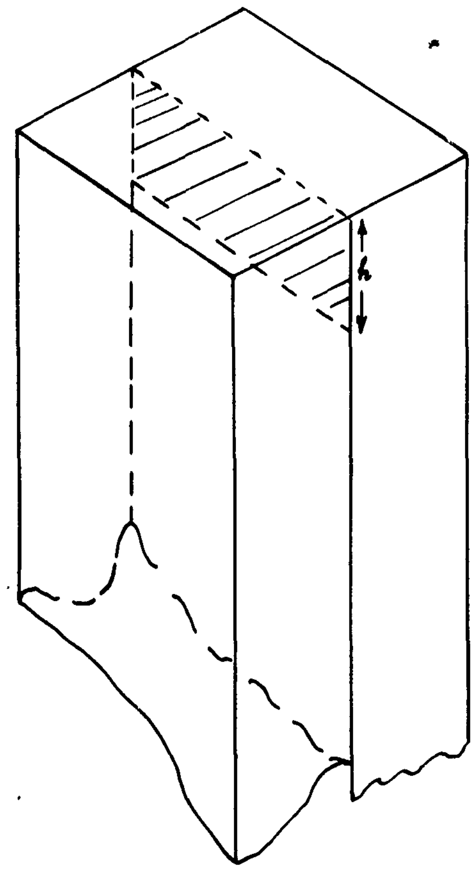
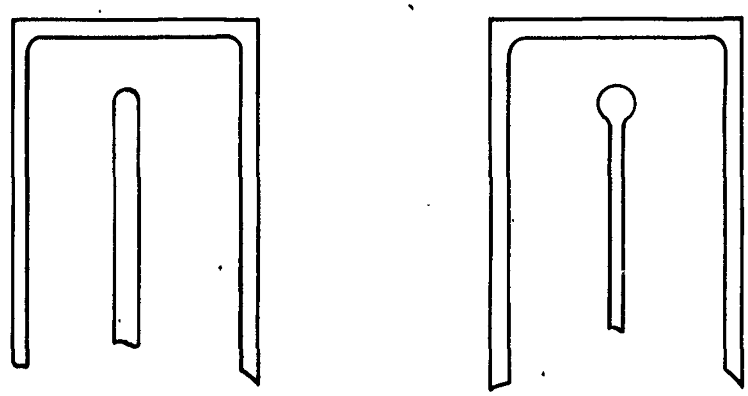


FIG. 7 SQUARE WAVEGUIDE CORNER



ROUND CORNERS AND COMMON WALL TO MINIMIZE SPARKOVER

EXAGGERATE RADIUS TO FORM CAPACITIVE CYLINDER.

FIG. 8 SIMULTANEOUSLY MATCHING SQUARE CORNER AND RAISING BREAKDOWN POWER

RX2-61-3

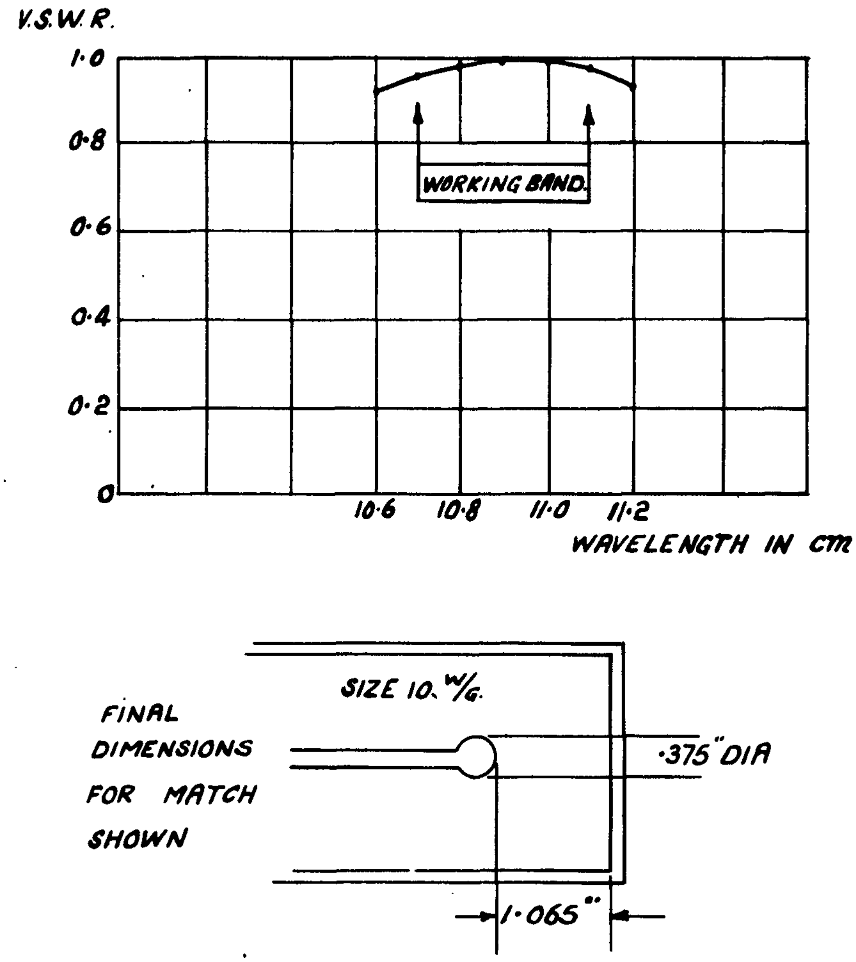


FIG. 9 V.S.W.R. OF SQUARE CORNER

RX2-61-3

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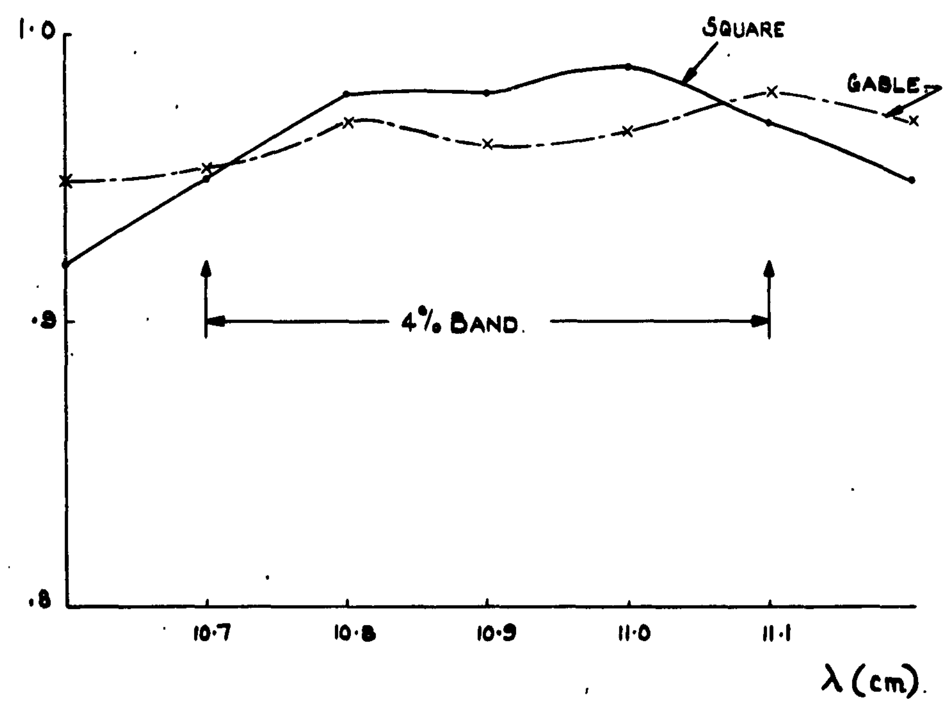
FIG. 10 V.S.W.R. OF SQUARE AND GABLE 180° CORNERS



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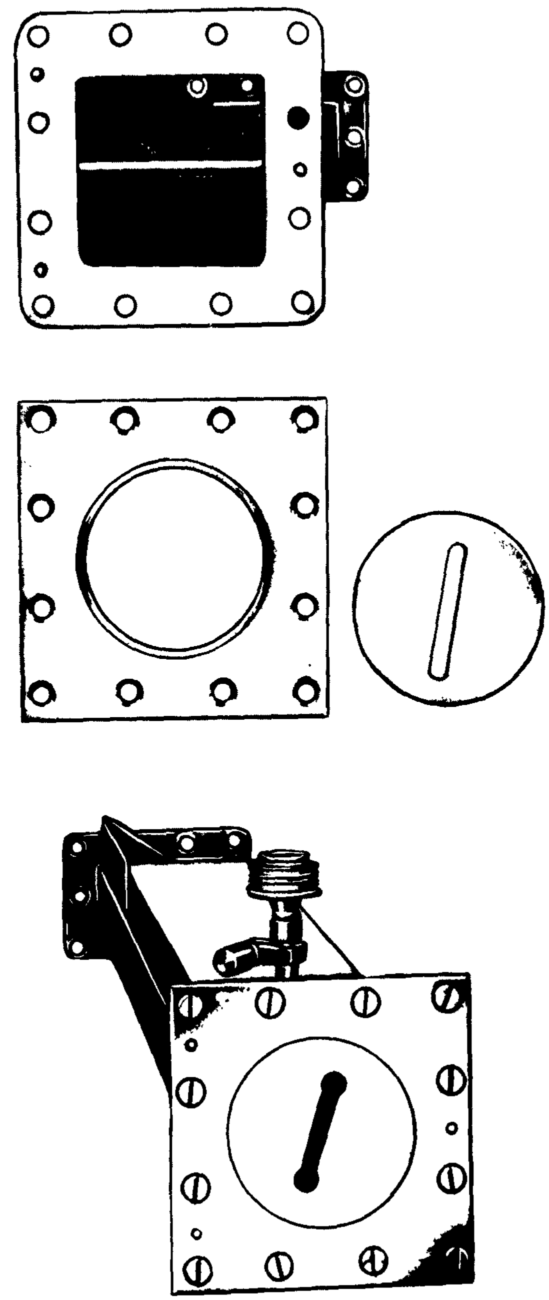
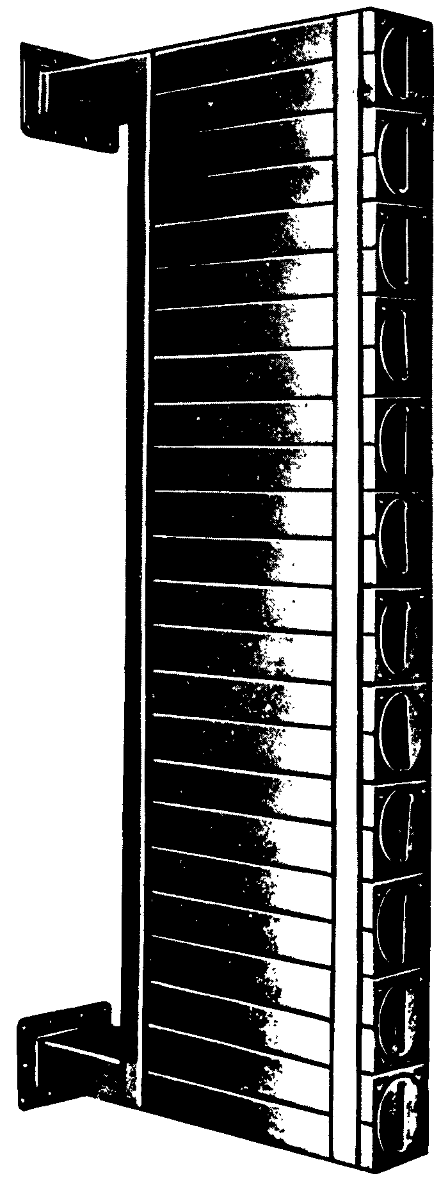


MATCHED 180° CORNER WITH
ROTATABLE SLOT

RX2-61-3

L62/251

12



12 - SLOT ARRAY WITH SQUARE CORNERS

RX 2-61-3

L62/252

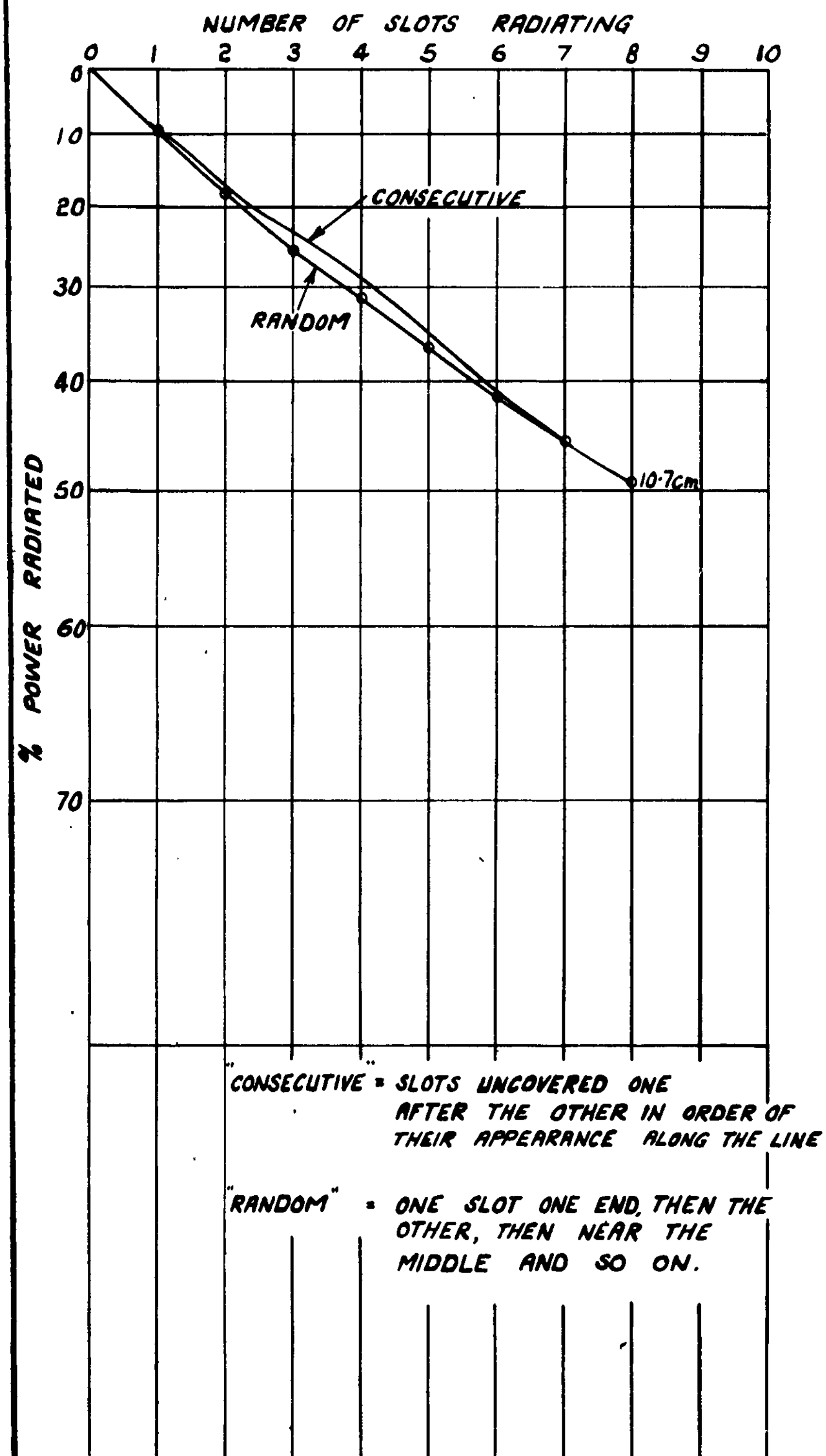


FIG. 13 TYPICAL INCLINATION OF 15°

RX2-61-3

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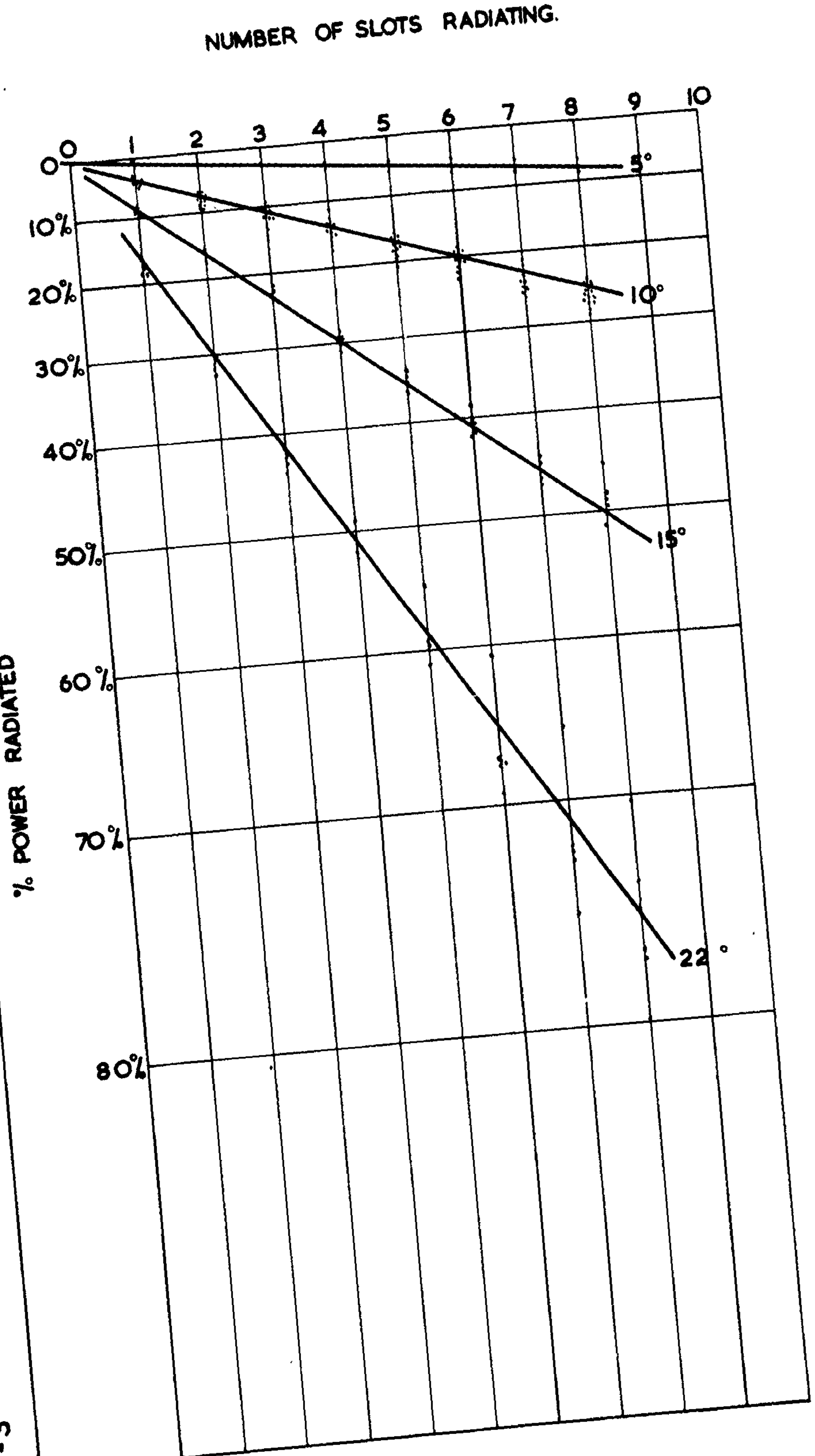


RX2-61-3

A.S.W.E. DATE 11.11.60 TR CH. APP. DRG. No.

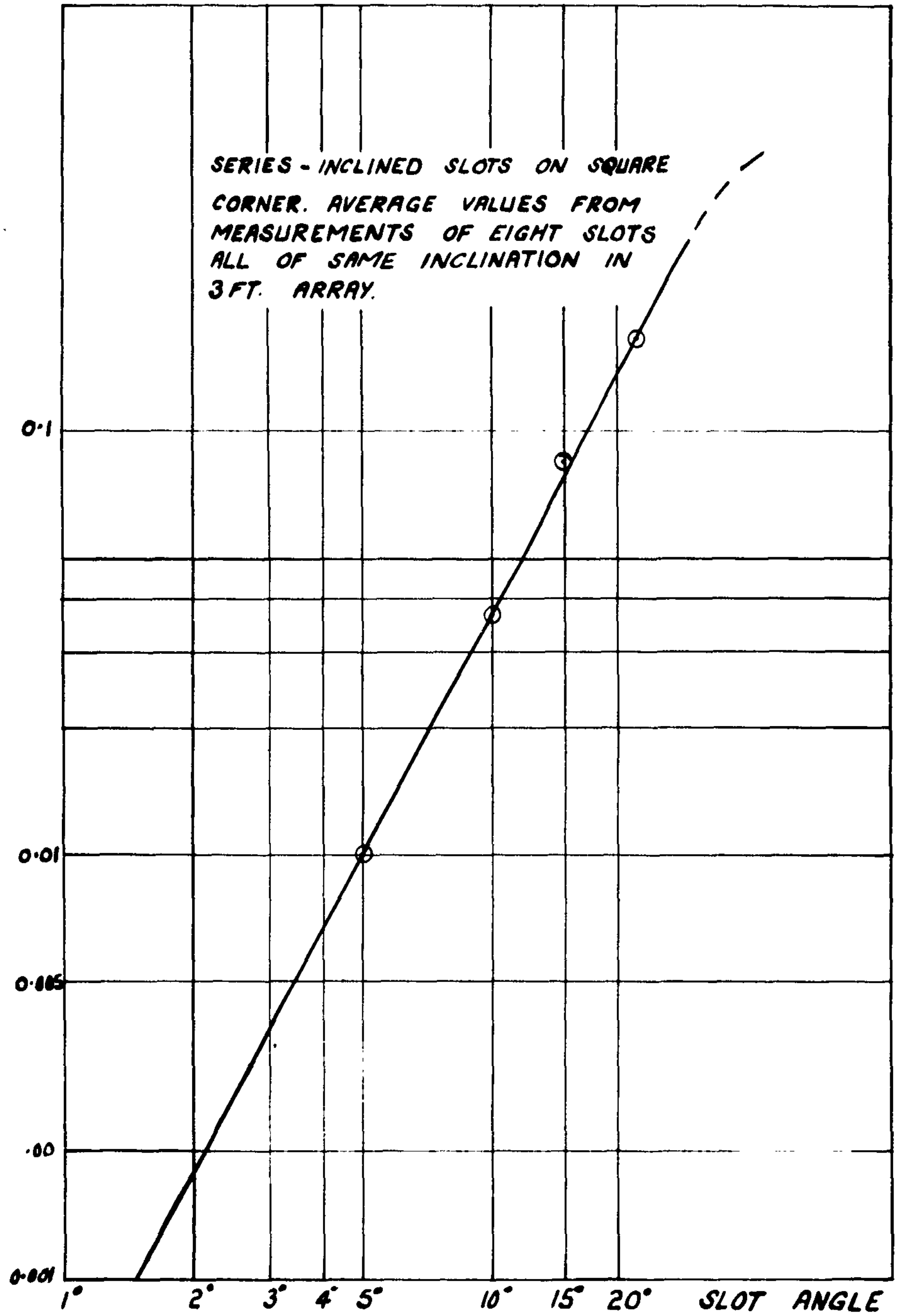
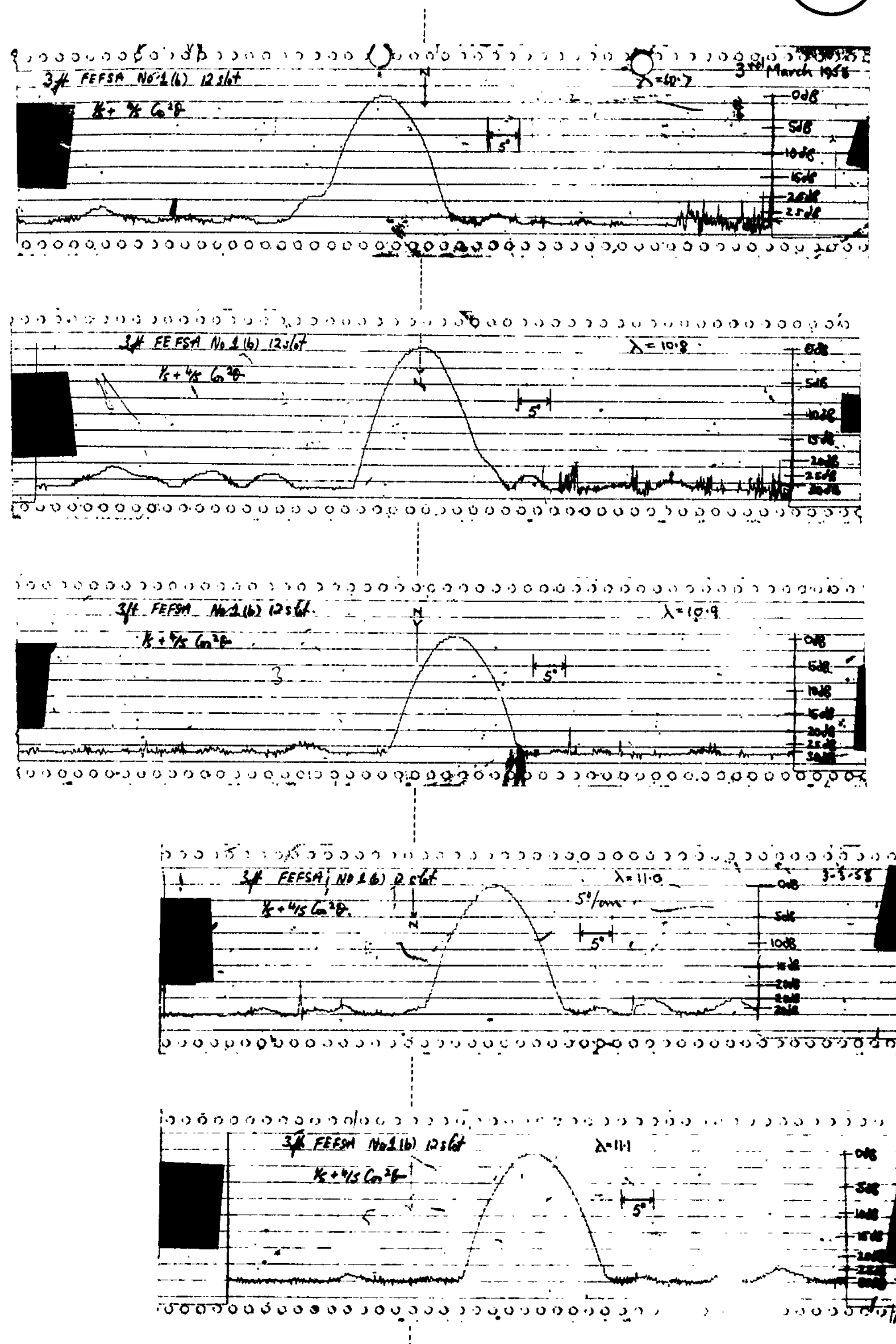


FIG. 15. NORMALIZED CONDUCTANCE OF SINGLE SLOT AGAINST ITS ANGLE OF INCLINATION

RX2-61-3



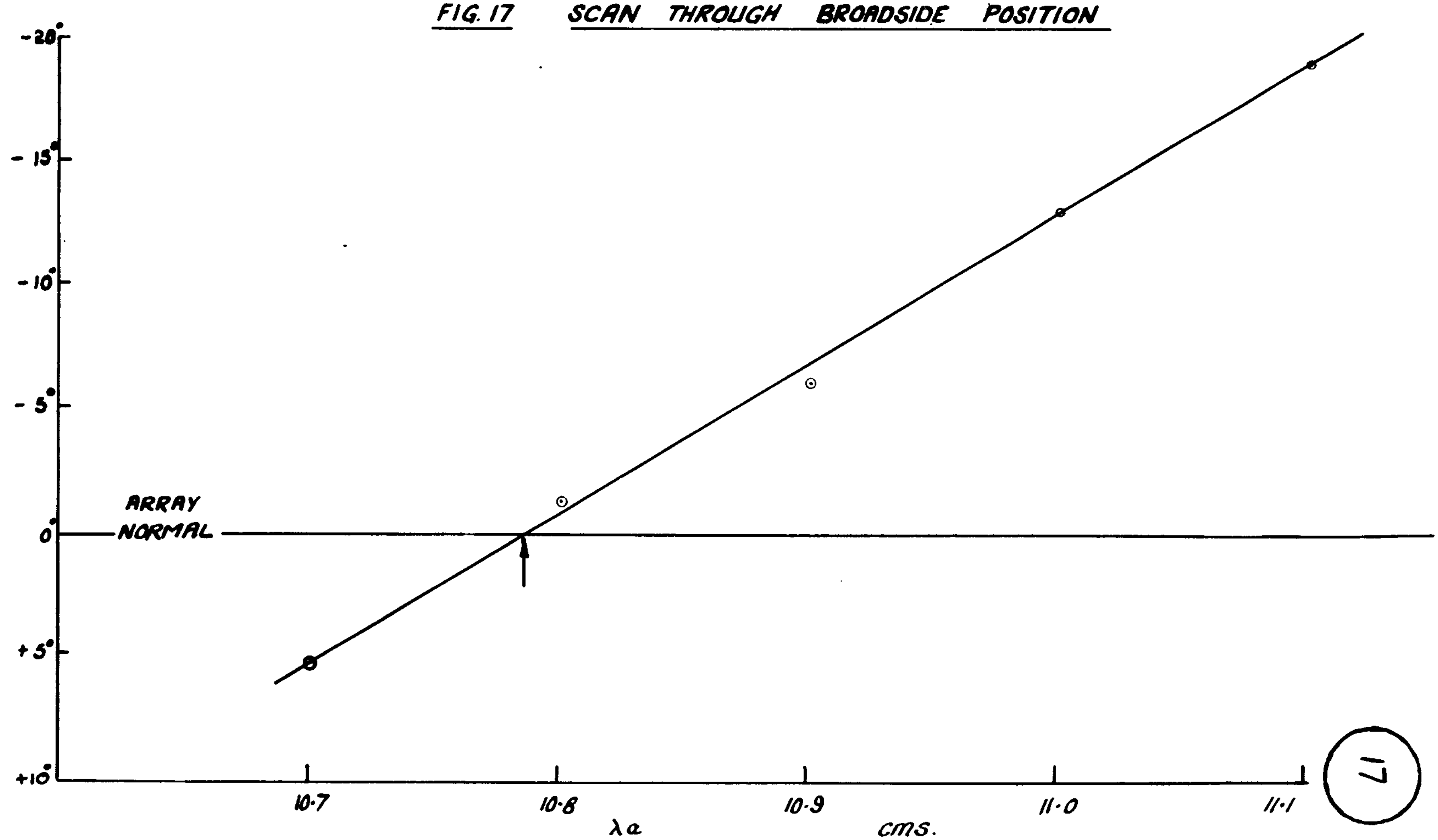
RX2-61-3

RADIATION PATTERNS SHOWING SCAN OF ARRAY WITH 12 SLOTS GIVING DISTRIBUTION $\frac{1}{5} + \frac{4}{5}\cos^2$

L60/439

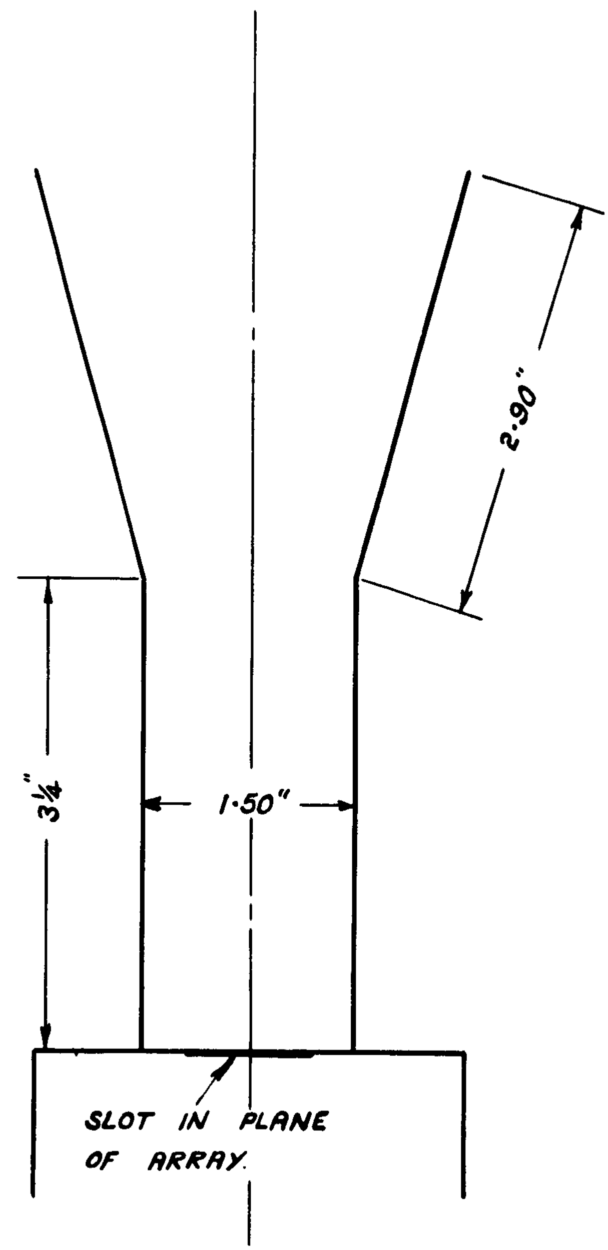
RX2-61-3

FIG. 17 SCAN THROUGH BROADSIDE POSITION



A.S.W.E. DATE 31-3-60 TR H.T.H./CH APP DWG No. A 263009

CROSS SECTION OF 12-SLOT ARRAY



RX2-61-3

A.S.W.E. DATE 27·9·60 TR [illegible] CH APP DWG No. A [illegible]

12 - SLOT ARRAY WITH FLARE

RX 2-61-3

L62/253

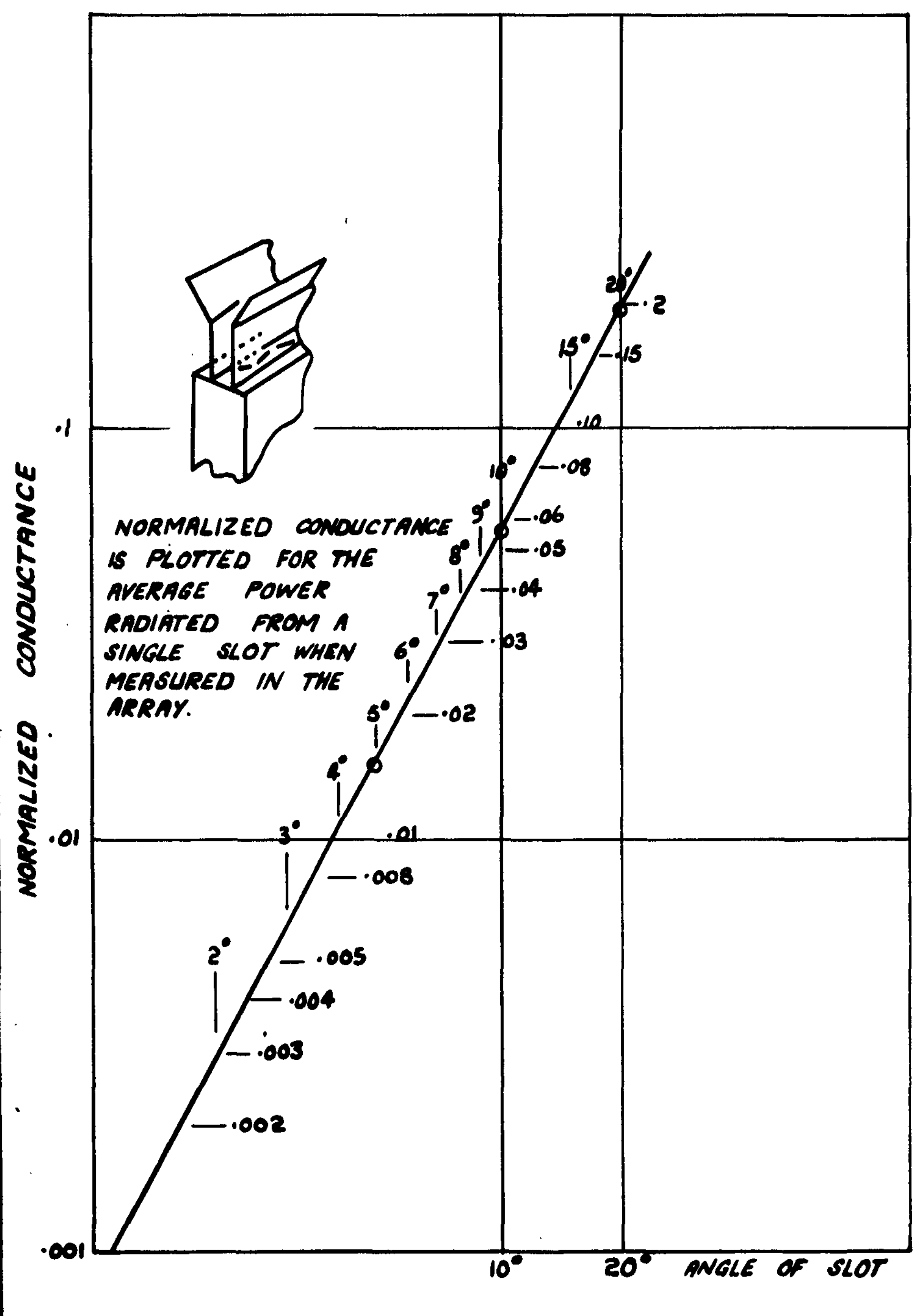
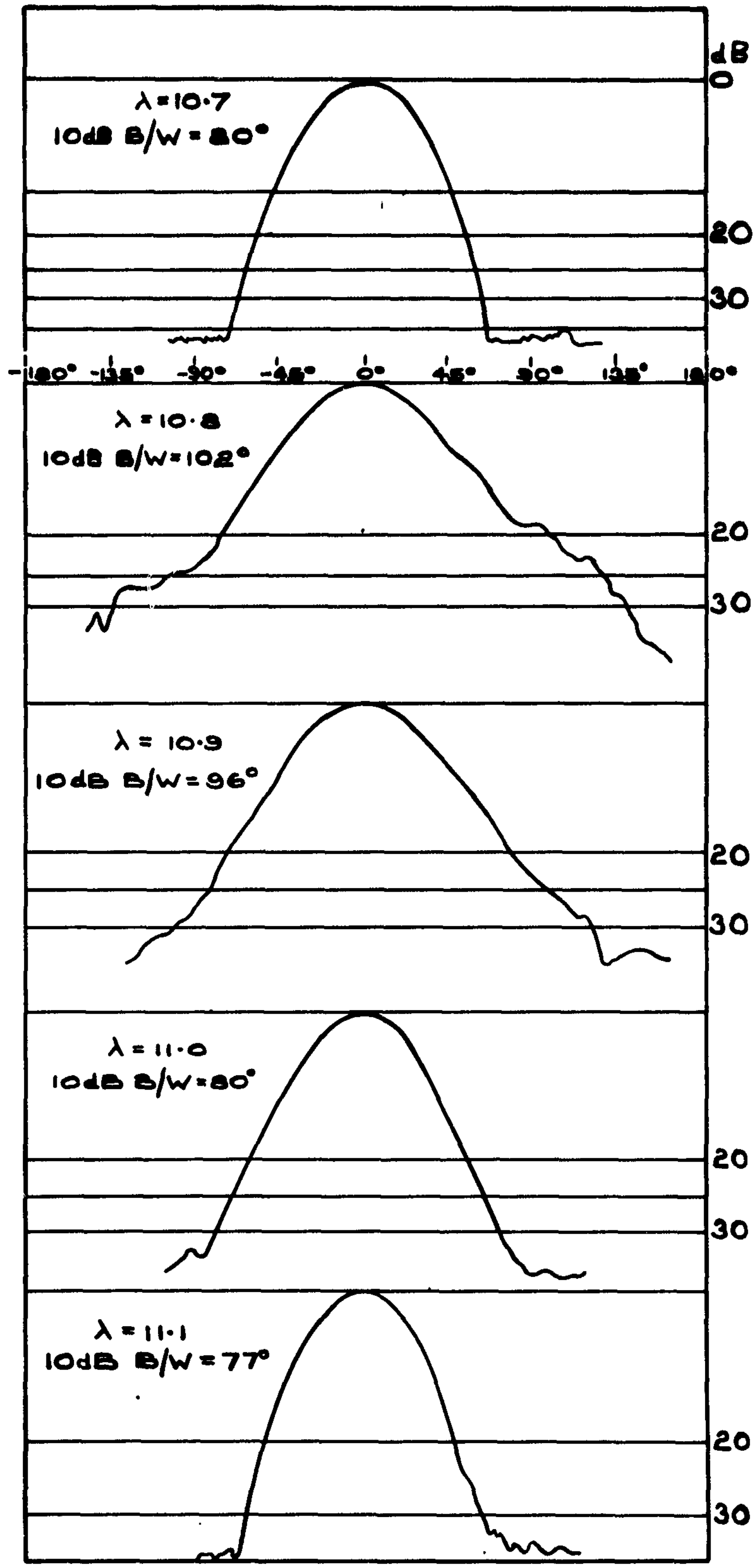


FIG. 20 ARRAY OF SLOTS WITH FLARE

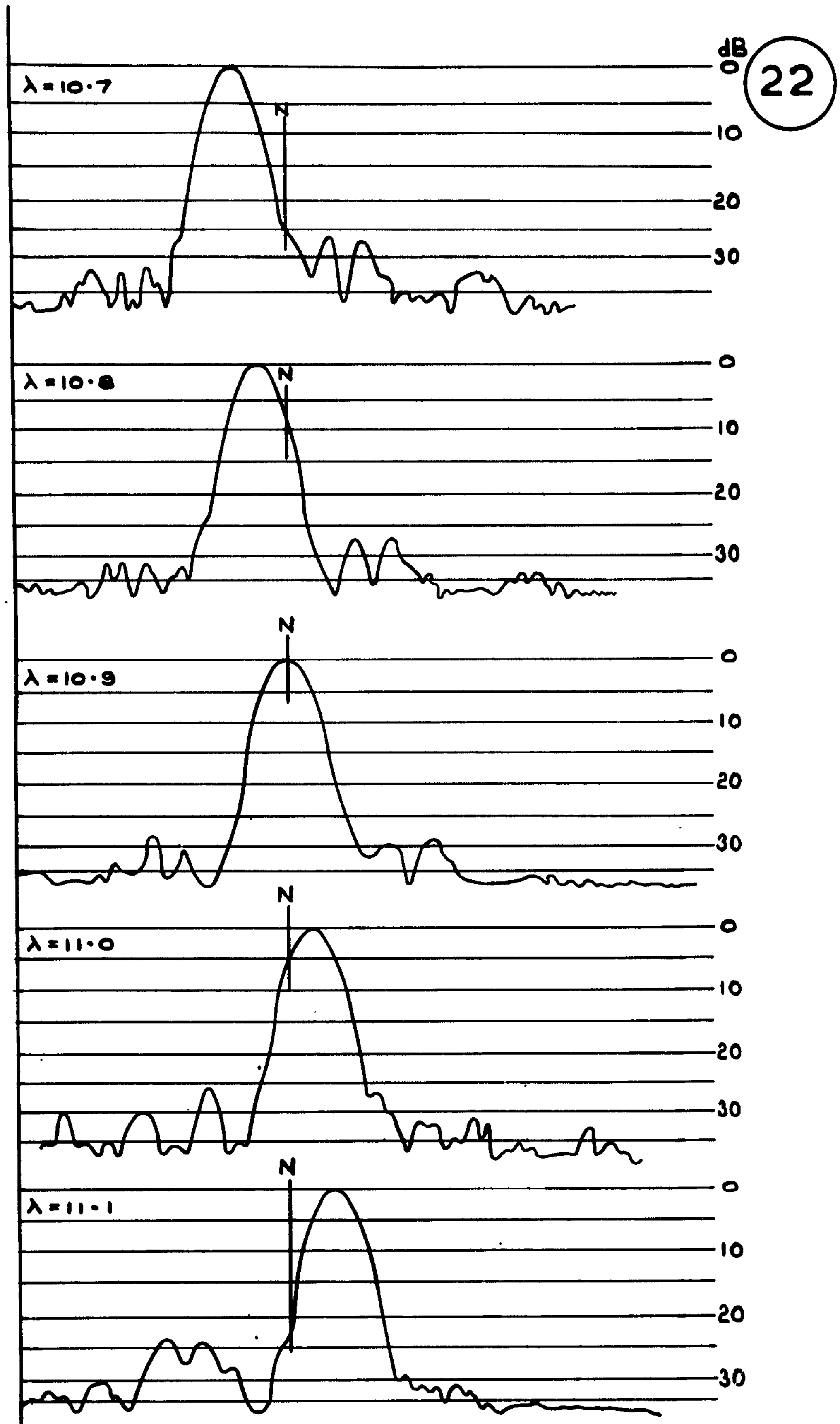
RX2-61-3

TRANSVERSE PATTERNS OF ARRAY WITH FLARE.



RX2-61-3

A.S.W.E. DATE TR. CH. APP. DWG. NO. A.263012

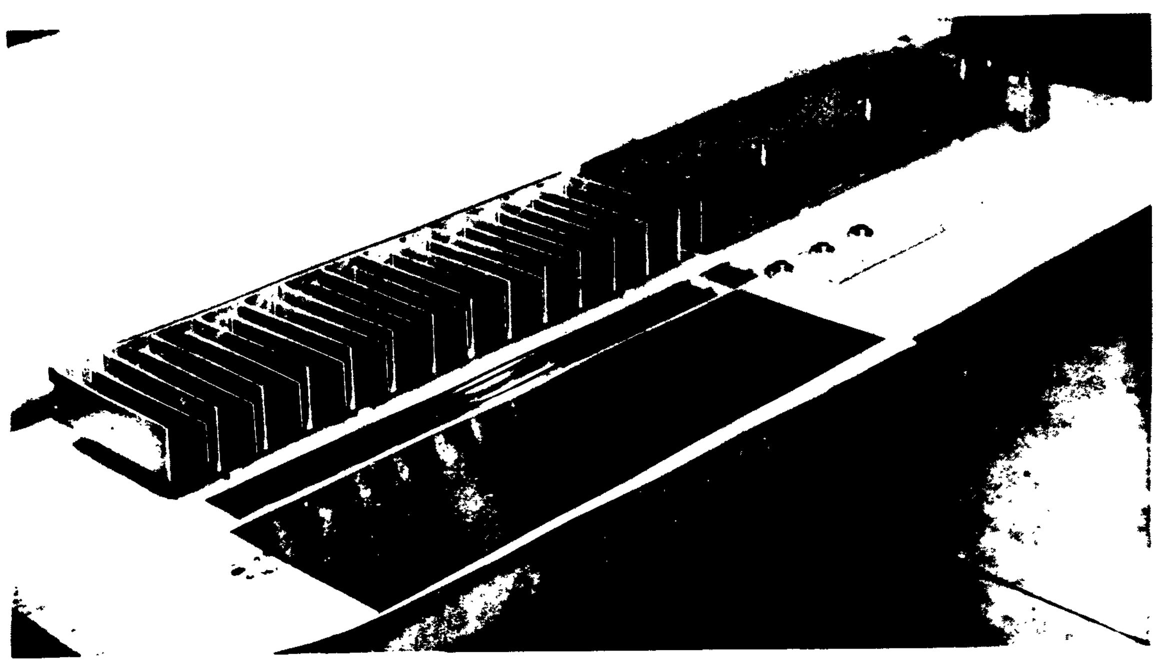


RX2-61-3

3FT. ARRAY OF 12 SERIES INCLINED SLOTS ON FLAT CORNERS.
(BEAM IN TRANSVERSE PLANE RESTRICTED WITH FLARE)

A.S.W.E. DATE TR. CH. APP. DWG. No. A.263013

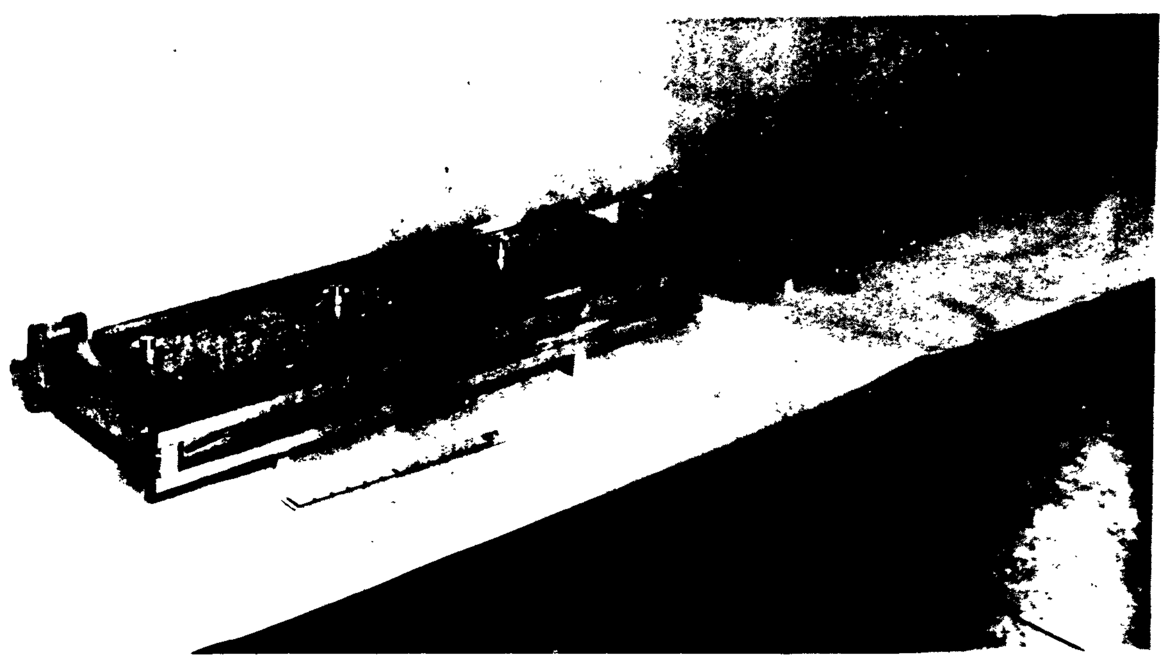
RX2-61-3



A SECTION OF 50-SLOT ARRAY

L62/254

RX2-61-3



A SECTION OF 50-SLOT ARRAY SHOWING RADIATING SLOTS

L62/255

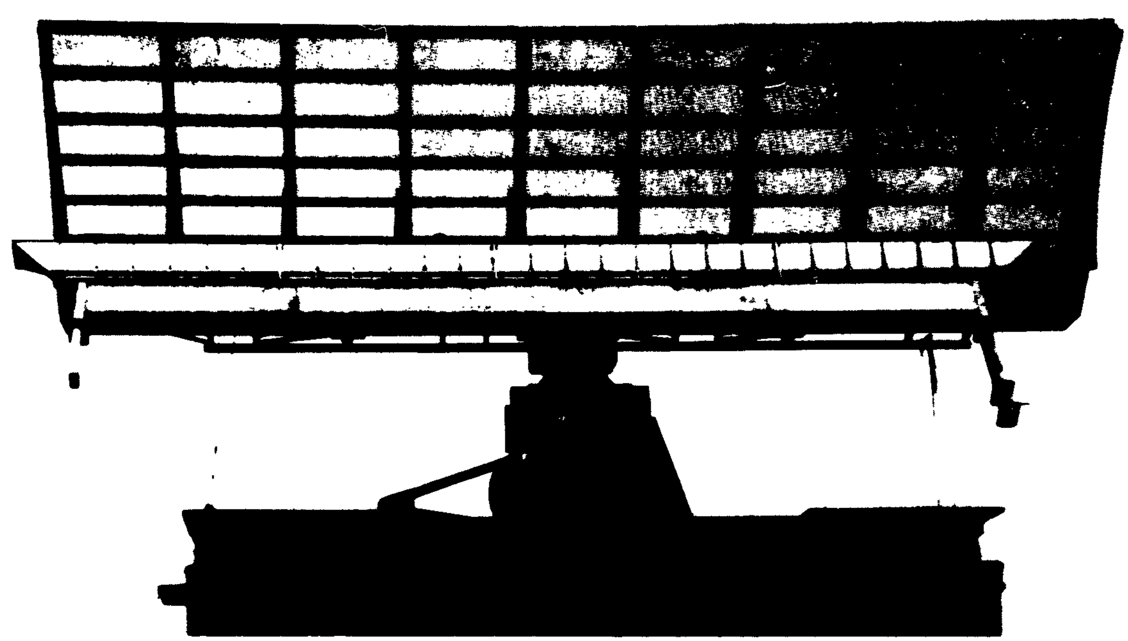
24

RX 2-61-3

A SECTION OF 50-SLOT ARRAY SHOWING
NON-RADIATING SIDE OF ASSEMBLY

L62/256

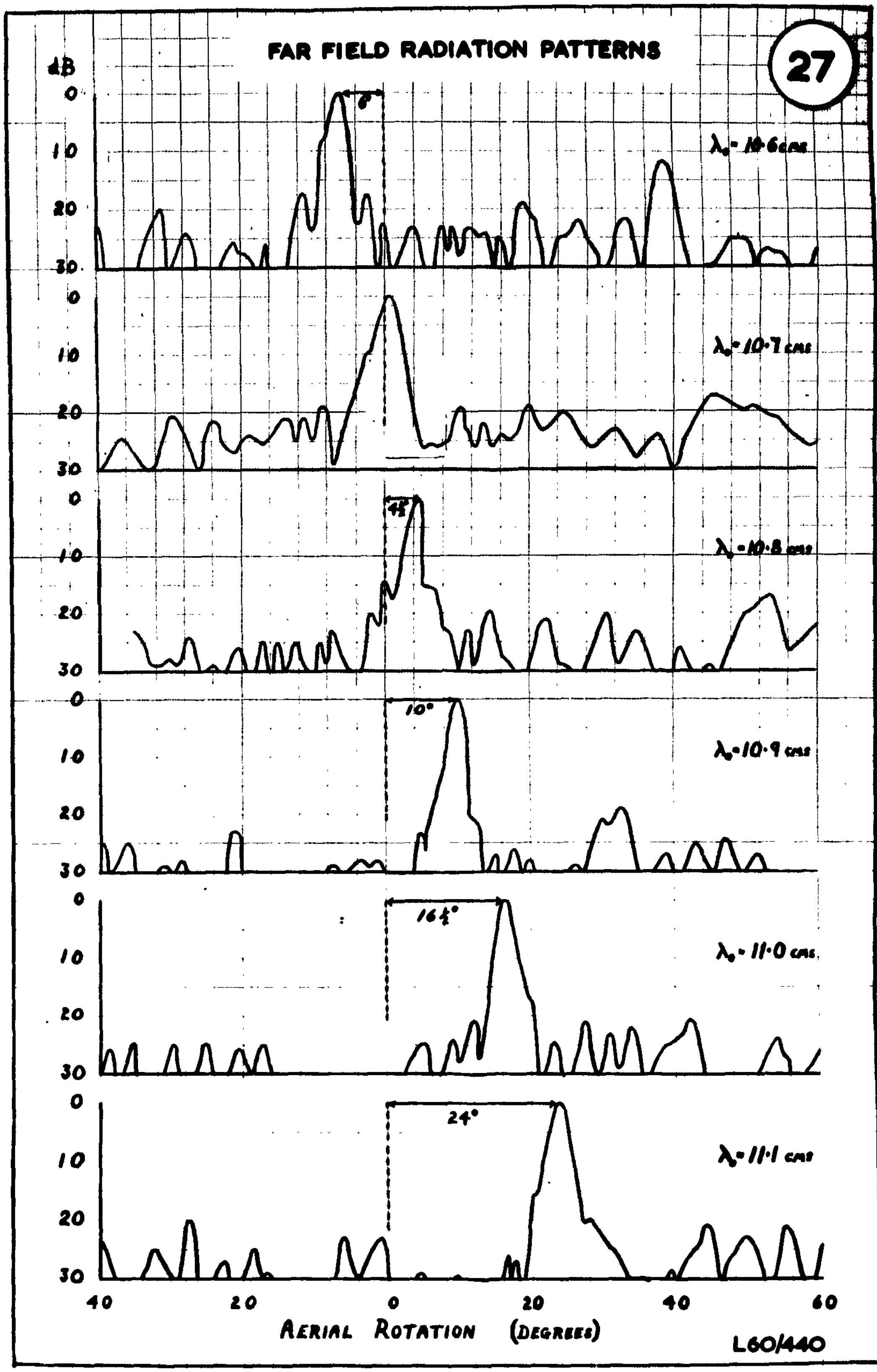
RX 2-61-3



50–SLOT ARRAY ASSEMBLED AT FOCUS OF PARABOLIC MIRROR

L62/257

26



FAR FIELD RADIATION PATTERNS
27
dB
0
10
20
30
8°
λ₀ = 10·6 cms
λ₀ = 10·7 cms
4½°
λ₀ = 10·8 cms
10°
λ₀ = 10·9 cms
16½°
λ₀ = 11·0 cms.
24°
λ₀ = 11·1 cms
40
20
0
20
40
60
AERIAL ROTATION (DEGREES)
L60/440

RX2-61-3

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AD#: AD0343597

Date of Search: 13 May 2009

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